GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-21-616 R58480A0 GTRI/~~GIT~~ DATE 10/24/84

Project Director: Dr. J. A. Connelly School/~~Lab~~ EE

Sponsor: Honeywell Inc., Underseas System Division 600 Second Street Northeast Hopkins, MN 55343

Type Agreement: Unnumbered Research Agreement

Award Period: From 9/15/84 To ~~12/30/84~~ 2-15-85 (Performance) 12/15/84 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 24,495	$ 24,495
Funded:	$ 24,495	$ 24,495

Cost Sharing Amount: $ N/A Cost Sharing No: ______

Title: Sea Water Bulk Sensor Design

ADMINISTRATIVE DATA

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Defense Priority Rating: ______

Military Security Classification: ______

(or) Company/Industrial Proprietary: Non-Disclosure agreement

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with none proposed

COMMENTS:

P.O. No. 130000 is referenced in the agreement, however, Mr. Pewewardy did not send the P.O. because he thought the research agreement should be sufficient. Invoices should reference P.O. No. 130000 when submitted for payment.

OCT 1984 Research Reports Office

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 3/5/85

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udes Subproject No.(s)

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nsor Honeywell, Inc. Underseas System Division

le Sea Water Bulk Sensor Design

fective Completion Date: 2/15/85 (Performance) 2/15/85 (Reports)

ant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
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SEA WATER BULK SENSOR DESIGN

by

J. A. CONNELLY

and

G. J. FISHER

FEBRUARY 1985

HONEYWELL, INC.
UNDERSEAS SYSTEMS OPERATIONS
600 SECOND STREET, N.E.
HOPKINS, MN 55343

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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HONEYWELL SEA WATER SENSOR REPORT

1.0 Introduction

This is the final report of work performed by J. Alvin Connelly and Gregory J. Fisher for the Underseas System Operations of Honeywell under Project Number E-21-616 R58480A0. The effort reported here investigated the design and testing of a sea water bulk sensor.

The remainder of this report is organized as follows: Section 1 defines the problem and discusses the major objectives of the study and provides background information relative to determining overall system requirements. Section 2 presents three alternate probe geometries which were deemed to improve detection of bulk sea water. Experimental test results on the present probe and these alternate configurations are also given in Section 2. The Wien Bridge oscillator is analyzed in Section 3 using conventional circuit analysis techniques and using the SPICE computer simulation program. Data from these analyses are compared with that obtained from experimentation using a brass board supplied by Honeywell. Results, conclusions, and recommendations are presented in Section 4. Appendixes A.1 through A.3 contain details of the supporting SPICE models used in the circuit analysis developed in Section 3.

1.1 Statement of the Problem

At the present time, Honeywell has developed a sensing system employing a parallel wire probe as part of a bridge circuit to detect conductivity changes when water enters a chamber. This chamber remains hermetically sealed until the torpedo is launched. Drop tests have shown that this chamber rapidly fills with water, and "sea sense" is detected within 20 ms of water entry.

It was felt that the present sea sense design may be susceptible to false outputs since it monitors only the resistance between two probe wires. A different type of probing geometry and/or sensing system would be capable of distinguishing between large and small amounts of fresh and sea water.

1.2 Objectives

The objective of this research is to design, build, test and evaluate a salt water bulk sensor for use in the ALWT. The complete system consists of a probe configuration and signal processing electronic circuitry capable of sensing the presence of a bulk of salt water. A major emphasis of this research was the probe configuration used to sense the presence of sea water. Alternative geometries to the open, parallel wire presently employed were designed and evaluated. A probe capable of sensing capacitive effects of sea water was also designed, analyzed, and evaluated. Conclusions from this study indicate that an alternative probe configuration will improve bulk sea water sense.

2.0 Evaluation of Sea Water Sensing Probe Structures

The existing sea water sensor detects the presence of sea water using a resistive approach. An evaluation of this approach and a discussion of limitations are made in this section along with a proposal of alternate resistive sensor geometries. The feasibility of a sensor design based on a capacitive approach is also discussed.

2.1 Results of Current Sea Water Sensor Tests

The sea water sensing circuit detects the presence of sea water through the use of an impedance bridge and a resistive sensor. The sensor, shown in Fiqure 2-1, consists of two parallel metal runs on a section of flexible printed circuit board material (flex board). The results of resistance tests perfomed by Honeywell personnel and by the investigators appear in Table 2-1.

Table 2-1 Sensor Tape Test Results

	Previous Honeywell Results (ohms)			Current Test Results (ohms)	
	3.5% Saline	0.2% Saline	Tap Water	Sea Water	Tap Water
One Drop Test	78	1.03 k	6.8 k	330	15.5 k
Immersion Test	4.7	44.3	343	40	2.8 k

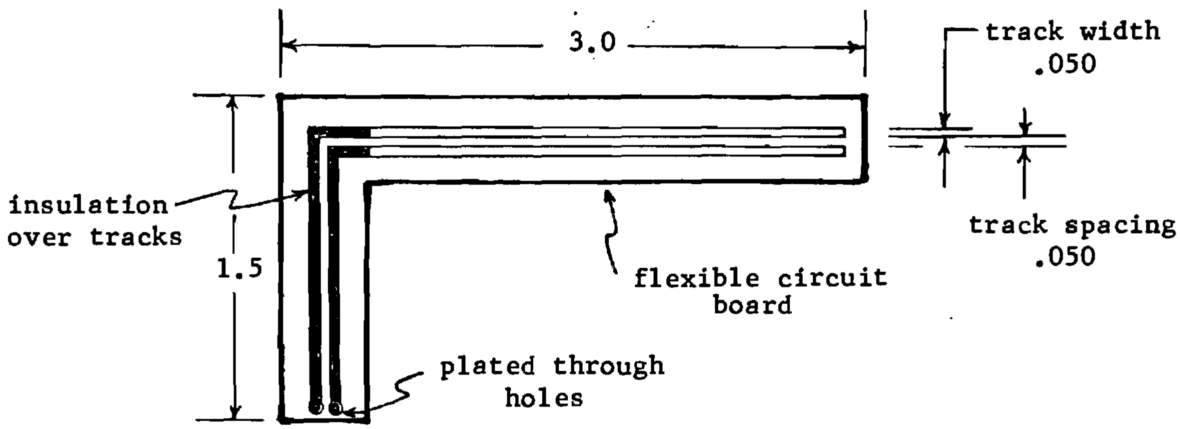


Figure 2-1 Sea Water Sensing Tape
(typical dimensions in inches)

The current results listed are the average of a number of trials performed using room temperature water with the sea water samples obtained from Melbourne, Florida. Measurements were taken with a Hewlett-Packard 4332A LCR Meter at a measurement frequency of 1 kHz. The discrepancies between the Honeywell and current test results listed are due to a number of factors including differences in measurement and test techniques, the varying properties of the tap water used and the fact that the sea water samples probably have a salinity differing somewhat from 3.5%. These tests are not intended to give an absolute resistance value for a threshold level; instead, these test results allow the present sensor tape design to be evaluated and basic limitations pointed out.

The sensor tape has been designed with four system criteria in mind:

1) With the tape in open air the measured resistance should be above the threshold value with circuitry holding a torpedo fire signal in a disable state.

2) If the tape is immersed or partially wetted by fresh water the measured resistance should be greater than the threshold value. Again, a torpedo fire signal is held at a disabling state.

3) If the tape is wetted by an equivalent of only one drop or less of sea water the measured resistance remains above the threshold value with a torpedo fire signal in a disable

state.

4) If the tape is wetted by some amount of sea water greater than one drop the measured resistance should equal or be less than the threshold value and a torpedo fire signal should be enabled.

These criteria suggest that the measured resistance for a quantity of less than one drop of either fresh or sea water be much higher than the threshold resistance value and that immersion in fresh water should also yield a resistance higher than the threshold. The sensor test results can be used to form a ratio of the one drop resistance value to the immersion value for each of the water samples. These ratios are shown in Table 2-2.

Table 2-2 One Drop-to-Immersion Resistance Ratios

Water Sample	R drop/R immersion
3.5% Saline	16.6
0.2% Saline	23.3
Tap (Honeywell)	19.8
Sea Water (Fla.)	8.3
Tap (Ga. Tech)	5.5

The present geometry of the sensor tape gives ratios of one drop resistance to immersion resistance from a low of 5.5 to 23.3. This range, which represents about an order of magnitude difference, may not be sufficiently high to give reliable operation. A resistive sensor geometry should be designed to significantly increase the one drop resistance value while maintaining an immersion resistance of less than 5 kohms.

2.2 Alternate Resistive Sea Water Sensing Tape Geometries

In this section a modified resistive sea water sensor design is presented. The sensor modifications were made with two goals in mind:

1) any sensor modification should be functionally compatible with the existing sea water sensing circuitry and should require a minimum of component changes,

2) the existing sensor tape physical design (conductive tracks on flexible circuit board) and physical size should be used to avoid changing the sensor housing design.

With these restrictions on any redesign, the two parameters available for modification are the conductive track pattern and the pattern of the insulation covering the tracks. Figure 2-2 shows a sensor tape with a modified conductive track and insulation pattern. Each track has two areas where the insulating material is removed. With the tape curled and placed in the sensor tape housing, the exposed sections are centered 90 degrees apart as shown in Figure 2-3. This design is intended to give a large measured resistance, essentially an open circuit condition, if an equivalent of one drop or less of either fresh or sea water wets the sensor tape. The distance between the exposed areas should be large enough so one drop of water cannot form a conductive path between the two tracks. Two exposed sections are provided on each track to account for the possibility that upon the firing of the torpedo the canister may not completely fill with water

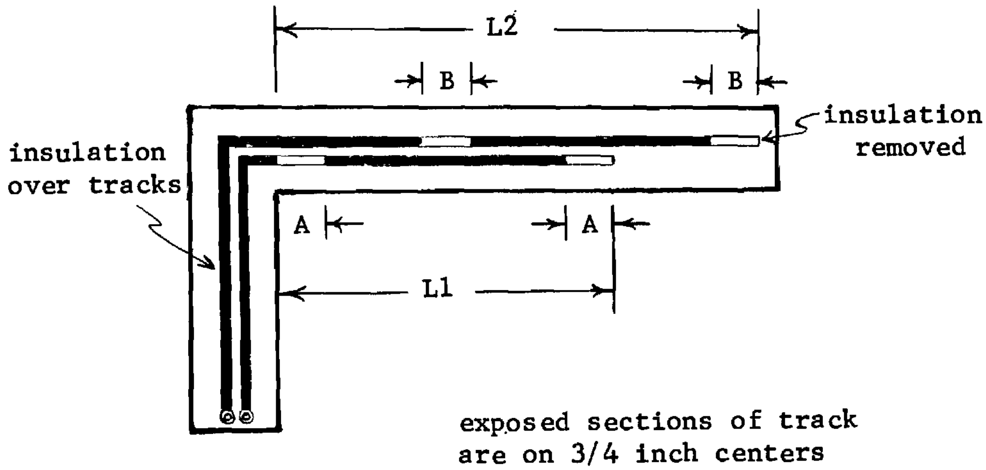


Figure 2-2 Modified Sea Water Sensor Tape

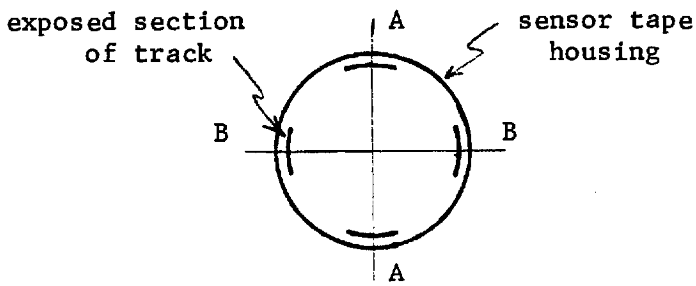


Figure 2-3 Positioning of Exposed Sections of Sensor Tape in Tape Housing

due to a trapped air bubble. Figure 2-4 shows a sensor tape with three sections of insulation removed from each track. This design is more forgiving of a trapped air bubble but requires closer spacing between exposed track areas.

Four test probes were fabricated using flexible circuit board material and a standard printed circuit board etching process. Table 2-3 lists the dimensions of each probe according to Figures 2-2 and 2-4. Three tapes were made with two exposed track areas while one tape was maded with three exposed areas per track. For each tape an immersion resistance was measured and the resistance values between adjacent sets of exposed areas was measured (this was done by covering the tape with just enough water to form a conductive path between a single set of exposed sections). The data in Table 2-4 and Table 2-5 form the results of the tests with the resistance values for a single set of exposed areas calculated as an average of the values measured for each tape. The tests were again done using room temperature water with the sea water samples obtained from Melbourne, Florida. The saline solutions consist of salt (NaCl) dissolved in deionized water.

Table 2-3 Dimensions of Sensor Tapes (inches)

Sensor Tape	A	B	L1	L2
1	1/8	1/8	1 5/8	2 3/8
2	1/4	1/4	1 3/4	2 1/2
3	1/4	1/2	1 3/4	2 5/8
4	1/8	1/8	2 1/8	2 5/8

Tapes 1, 2 & 3 based on Fig. 2-2
Tape 4 based on Fig. 2-4

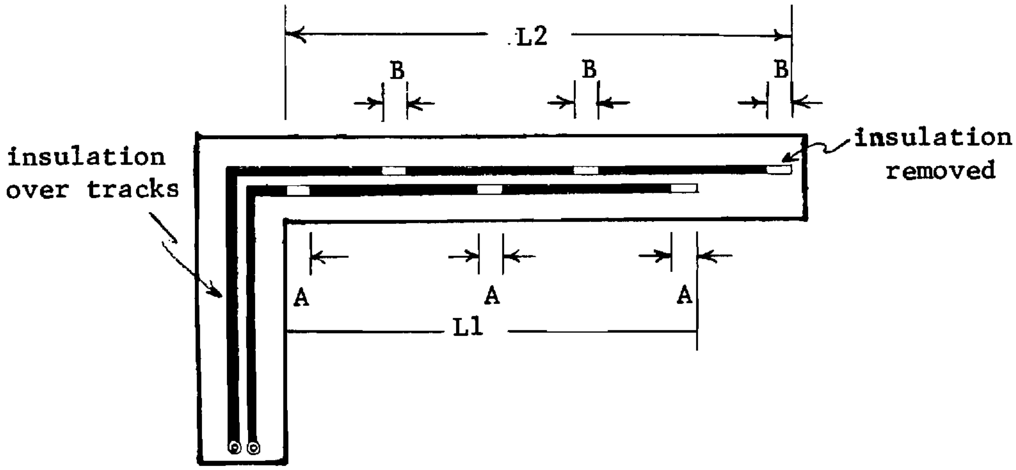


Figure 2-4 Sea Water Sensor Tape With Three Exposed Sections Per Track

Table 2-4 Sensor Tape Test Results

Sensor Tape	Resistance of Single Exposure Set		Immersion Resistance	
	Tap Water	Sea Water	Tap Water	Sea Water
1	125 k	917	15 k	240
2	152 k	733	13 k	105
3	87 k	493	12 k	120
4	153 k	1.42 k	13 k	220

The data listed in Table 2-4 and Table 2-5 indicate that the sensor tape designs tested do function as intended. The immersion resistances are higher than for the existing sensor tape yet remain within practical values. The resistances for conduction between a single set of exposed track sections vary between 400 ohms and 1.4 kohms depending on geometry and salinity. These values are sufficiently low to allow reasonable component values in the sea water sensing circuitry. An amount of water equivalent to about 2 or 3 drops of water was requred to form a conductive path between the exposed track areas on each tape tested. Any amount of water less than this resulted in open circuit conditions.

Table 2-5 Sensor Tape Test Results (Saline)

Sensor Tape	Resistance of Single Exposure Set		Immersion Resistance	
	0.2% Saline	3.5% Saline	0.2% Saline	3.5% Saline
1	6.9 k	989	1.0 k	330
2	4.0 k	440	530	140
3	2.9 k	395	400	90
4	3.7 k	501	450	100

2.3 Sensor Design Based Upon Capacitive Effects

The capacitive effects of the parallel wire probe of Figure 2.1 were studied based upon an analysis given by Corcoran and Reed [1]. Viewing the probe as a parallel wire transmission line, the wire-to-wire capacitance is given by

$$C_{w\text{-}to\text{-}w} = \frac{27.78\, er}{\ln \frac{D - w/2}{w/2}} \ \text{pF/meter} \qquad (2.1)$$

where D is the distance between wire centerlines, w is the wire width, and er is the relative dielectric constant of water. Using dimensions of D=0.1 inches and w=0.05 inches gives

$$C_{w\text{-}to\text{-}w} = 25.3\, er \ \text{pF/meter} \qquad (2.2)$$

The relative dielectric constant of distilled water was found to range between about 80 to 81.5, and the length of the wire tracks on the probe was measured to be about 0.0659 meters. With er=80, Equation 2.2 yields a probe capacitance of 133 pF when immersed in distilled water. At a frequency of 2 kHz, this probe would have a reactance of about 600 k ohms which would be in parallel with the resistance of the water. This resistance is known to be much smaller than the capacitive reactance. Hence, any attempt to sense capacitive changes using an open wire probe that also sensed resistance would be futile.

[1] Corcoran, G. F. and H. R. Reed, "Introductory Electrical Engineering," New York: John Wiley & Sons, Inc., 1957.

The exposed parallel wires of the flex board were sealed with mylar tape to prevent water contact. Two small wires of approximately 2 inch lengths were soldered to the plated through holes of the probe for electrical contact. The capacitance of this probe was measured to be 28 pF in air using a DORIC Model 130A capacitance meter. This is quite reasonable using Equation 2.2 and assuming an er value of the mylar tape to be approximately 15.

Next the probe was tightly fixed to a flat surface and single drops of tap water added across the tracks one at a time. Each drop of water added approximately 3 pF of capacitance. A maximum of seven drops of water could be positioned on the probe without two or more running together. This produced about 45 pF when all seven drops were present.

Additional tap water was added so that a continuous film of water covered most of the probe. Here the capacitance increased to about 74 pF. The probe was then coiled and insereted into a plastic cup and filled with tap water to cover all of the probe except the vertical section. The immersed probe capacitance increased to 82 pF. Finally about 1/4 teaspoon of table salt was added causing the capacitance to increase to 88 pF.

These tests were repeated several times with similar results using tap water and Melbourne sea water. Trends showing increasing capacitance with increasing water volume were very repeatable. Exact numerical capacitance values were not repeatable due mainly to an inability to accurately control water drop size and position.

A new probe configuration was designed as shown in Figure 2-5. It was thought that by extending amd interleaving the conductive tracks, a larger static capacitance would result as well as a larger capacitance change per water drop. This probe was tested in a similar manner to the parallel wire probes with almost identical results. The static probe capacitance in air was measured to be 9.2 pF. Each drop of tap water increased the probe capacitance by approximately 3 pF until 11 drops produced 42 pF and no more could be added. Completely covering the tracks with water raised the probe capacitance to approximately 69 pF. Again the trend of a semi-linear capacitance increase with water volume was apparent for this probe even though the total capacitance was less. This can be explained as follows. In an attempt to seal the tracks from water contact, the photoresistive sealant deliberately was not removed from the etched flex board. This substance together with the mylar tape increased the distance the field lines had to travel between tracks thereby decreasing the total capacitance.

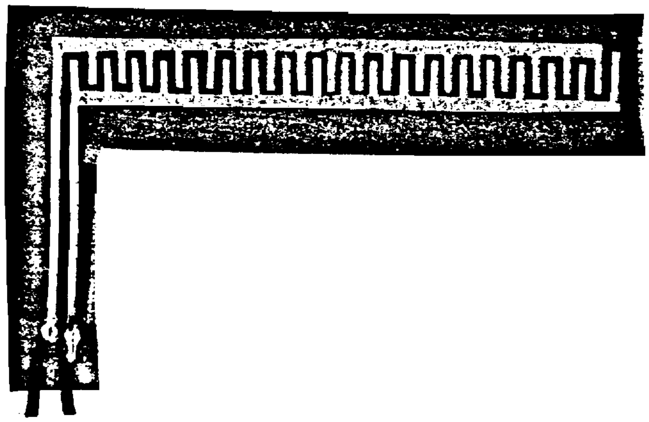


Figure 2-5 Capacitive Probe

3.0 Wien Bridge Oscillator

The sea water sensing circuit includes a Wien Bridge Oscillator with amplitude limiting circuitry. This section contains an analysis of the oscillator with an emphasis on the function of the amplitude limiting circuitry and the expected peak output voltage. A short derivation of the Wien Bridge Oscillator design equations is presented first. The amplitude limiting circuitry is then introduced with a simple calculation of the peak output voltage. Finally, results from the SPICE2.G.6 circuit analysis program are given and compared to both the actual circuit measurements and the simple calculation results.

3.1 Background Theory

A Wien Bridge Oscillator circuit similar to that used in the sea water sensing circuit is shown in Figure 3-1. The conditions required for oscillation can be derived by considering the ideal operational amplifier circuit having transfer functions

$$\frac{V+}{V_{OUT}} = \frac{1}{\Delta RC + 3 + 1/\Delta RC} \qquad (3.1)$$

$$\frac{V_{OUT}}{V-} = 1 + \frac{RF}{RIN} \qquad (3.2)$$

Combining the transfer functions into a closed loop feedback transfer function expressed as a magnitude and phase gives

$$|H| = \frac{\frac{RF}{RIN} + 1}{\left[9 + (\omega RC - 1/\omega RC)^2\right]^{1/2}} \qquad (3.3)$$

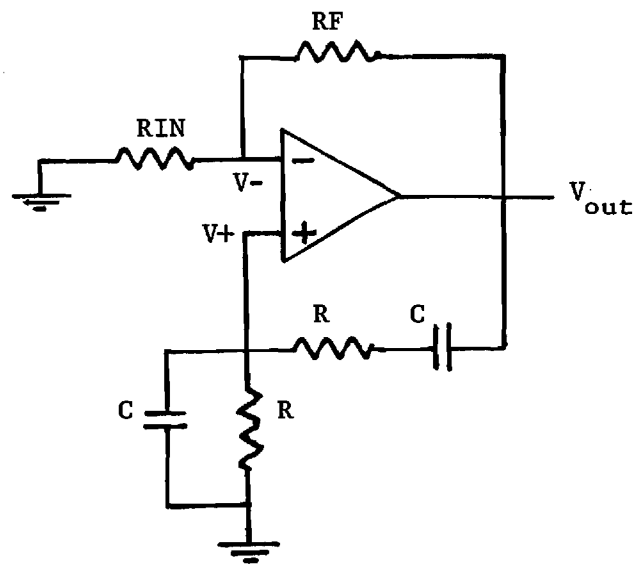


Figure 3-1 Wien Bridge Oscillator

$$\angle H = -\tan^{-1}\left[\frac{\omega RC - 1/\omega RC}{3}\right] \qquad (3.4)$$

The frequency of oscillation which results in the necessary 360 degree phase shift is given by

$$\omega = \frac{1}{RC} \qquad (3.5)$$

At this frequency the magnitude expression reduces to

$$|H| = \frac{1}{3}\left(\frac{RF}{RIN} + 1\right) \qquad (3.6)$$

For oscillations to be maintained, the resistors RF and RIN are chosen such that

$$\frac{RF}{RIN} + 1 > 3 \qquad (3.7)$$

3.2 First Order Calculation of Oscillator Peak Output Voltage

An amplitude limiting function is provided by the diode bridge and an additional resistor as shown in Figure 3-2. A first order approximation of the oscillator peak output voltage can be made using a few simplifying assumptions:

1) consider the zener diode DZ1 as ideal with a reverse breakdown voltage VZ,

2) diodes D1, D2, D3, D4 are described in forward bias conditions by the ideal diode equation

$$I = I_o \exp\left(\frac{Vq}{kT}\right) \qquad (3.8)$$

3) the oscillator output has only a single frequency component given by

$$f = \frac{1}{2\pi RC} \qquad (3.9)$$

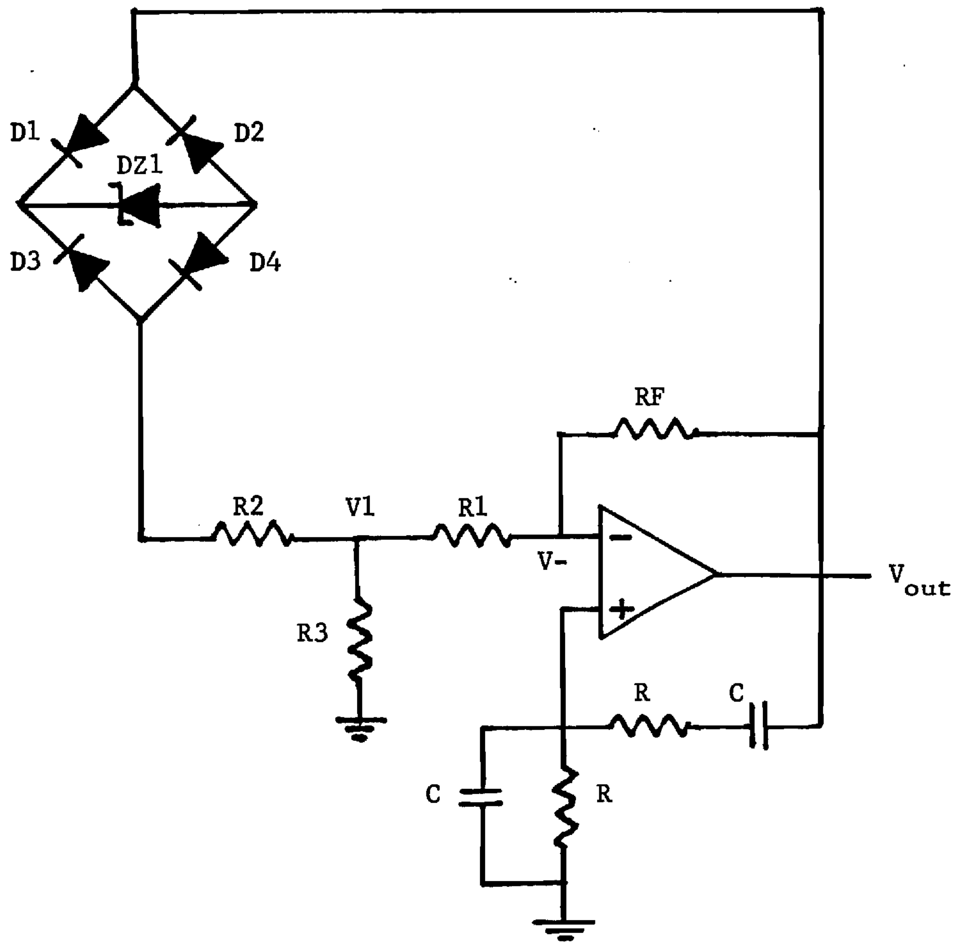


Figure 3-2 Amplitude Limited Oscillator

With the output voltage below a certain threshold voltage, Von, the diode bridge does not conduct current and has no effect on the oscillator output. An expression for this threshold can be found by noting that the voltage V- is given by

$$V- = \frac{1}{3} V_{OUT} \tag{3.10}$$

at the oscillation frequency. Assuming a diode turn on voltage of Vd, the output threshold voltage, Von, is given by

$$V_{ON} = \left(\frac{R3}{R1+R3}\right)\frac{V_{ON}}{3} + 2Vd + VZ \tag{3.11}$$

or

$$V_{ON} = (2Vd + VZ)\,\frac{R1 + R3}{R1 + 2R3/3} \tag{3.12}$$

Note that the diode current at turn on is assumed to be negligable.

Using the following circuit parameters, the output voltage at which the diode bridge begins to conduct can be calculated.

$$Vd = 0.6V \qquad VZ = 5.6V$$

$$R1 = 58A4 = 5.36\,k\Omega \qquad R3 = R57C6 = 1.33\,k\Omega$$

$$V_{ON} = 7.28\,V \tag{3.13}$$

The peak output voltage, Vmax, can be calculated by considering the diode bridge and the resistor R2 shown in Figure 3-2 as an equivalent time dependent resistance Req. The closed loop feedback transfer function is now modified and is given by

$$|H| = \frac{1}{3}\left[\frac{RF\,REQ}{REQ\,R3 + R1R3 + R1REQ + R3RF} + 1\right] \tag{3.14}$$

A steady state of oscillation is reached when

$$|H| = 1 \tag{3.15}$$

or

$$\frac{RF\,REQ}{REQ\,(R1 + R3) + R1R3 + R3RF} = 2 \tag{3.16}$$

Solving for Req yields

$$REQ = \frac{R3\,(R1 + RF)}{(RF/2) - (R1 + R3)} \tag{3.17}$$

For the sea water sensing circuit, the resistor values are:

$$\begin{aligned} R1 &= R58A4 = 5.36\ K\Omega \\ R3 &= R57C6 = 1.33\ K\Omega \\ RF &= R59A2 = 15.4\ K\Omega \end{aligned} \tag{3.18}$$

Now Req is evaluated,

$$REQ = 27.34\ K\Omega \tag{3.19}$$

The current through Req at the peak output voltage Vmax can be calculated using

$$VMAX - V1 = IREQ = IR2 + 2Vd + VZ \tag{3.20}$$

where

$$I = I_o \exp \frac{Vq}{kT} \tag{3.21}$$

The current I can be solved using the following equation and circuit values.

$$(REQ - R2)\,I_o \exp \frac{Vq}{kT} = 2V + VZ$$

$$R2 = R56B6 = 3.65\ K\Omega \qquad VZ = 5.6\ V$$

$$I_o = 10^{-14}\ A \qquad \frac{q}{kT} = 0.026\ V$$

An approximate solution is given by

$$I = 0.289\ mA \qquad V = 0.626\ V \tag{3.23}$$

or

$$VMAX - V1 = 7.9\ V \qquad (3.24)$$

Now, V1 is given by

$$V1 = \left[I + \frac{VMAX - V-}{RF} \right] R3 = \left[I + \frac{2}{3}\frac{VMAX}{RF} \right] R3$$

Solving for Vmax gives

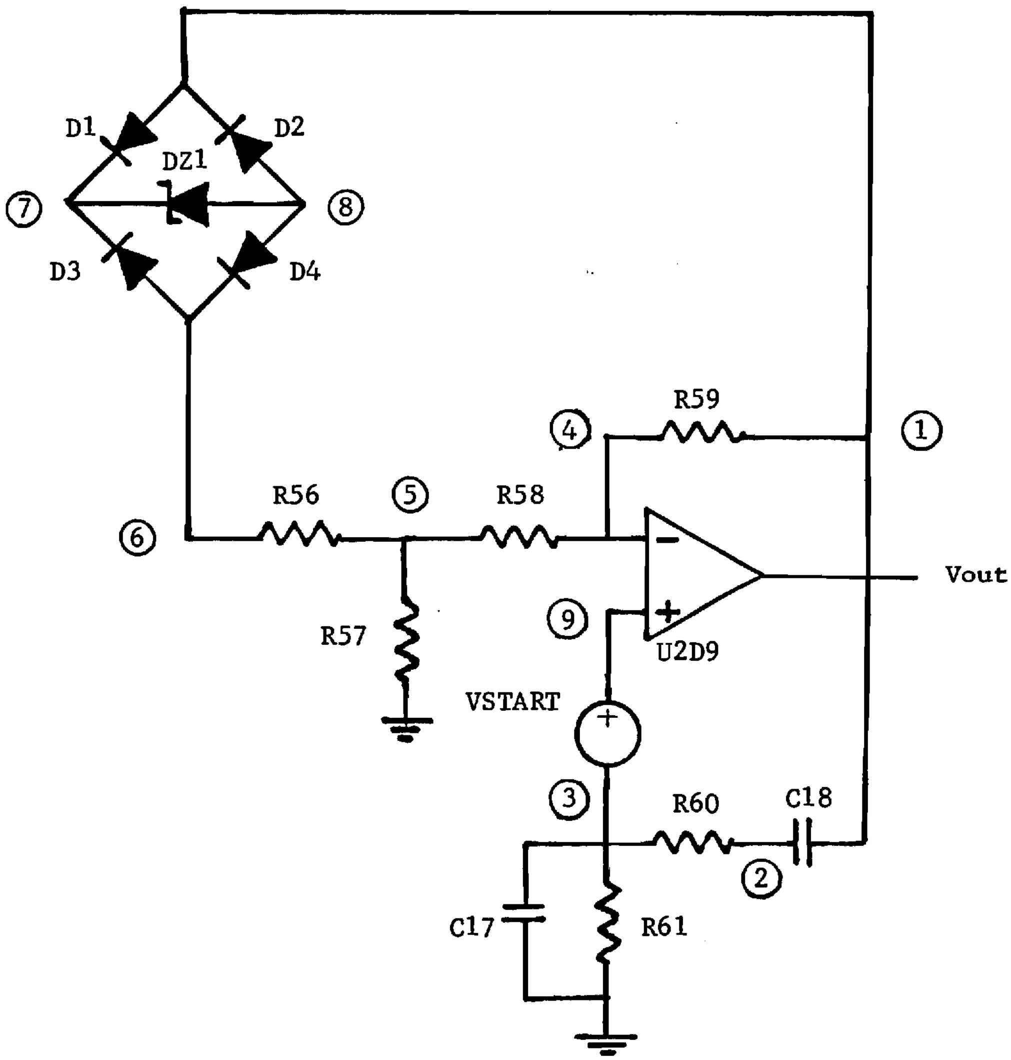
$$VMAX = \frac{7.9 + IR3}{1 - \frac{2}{3}\frac{R3}{RF}} = 8.79\ V \qquad (3.26)$$

3.3 SPICE2.G.6 Analysis of Wien Bridge Oscillator

An analysis of the oscillator circuit shown in Figure 3-3 was performed with SPICE2.G.6. A listing of the complete output file appears in Appendix A.3. The major results of the SPICE analysis are summarized below.

Output Voltage at Diode Turn On	Von = 7.2 V
Peak Output Voltage	Vmax = 9.93 V
Total Harmonic Distortion	THD = 8.4 %

The threshold voltage Von is taken to be the output voltage when the diode bridge current is approximately an order of magnitude less than the current flowing through the resistor R58.



R56 = 3.65 k
R57 = 1.33 k
R58 = 5.36 k
U2D9 = RM4156
R59 = 15.4 k
R60, R61 = 7.87 k
C17, C18 = 0.01 uF
◯ indicates node numbers

Figure 3-3 Oscillator Circuit used in SPICE Analysis

3.4 Measured Circuit Performance and Comparison of Analysis Results

A sample brass board implemention of the existing sea water sensing circuit was supplied by Honeywell for evaluation. Figure 3-4 shows the schematic of the circuit board and current component values. The results of the measurements are listed in Table 3-1 along with a summary of the results obtained with the first order calculations and the SPICE2.G.6 analysis.

Frequency values are as expected with the measured oscillation frequency well within the range allowed for by component tolerances.

The values shown for the output voltage threshold, which is defined here as the output voltage at which the diode bridge current is within an order of magnitude of the current through resistor R58 as labeled in Figure 3-3, show the most variation among the results listed. This is due to the simplifying assumptions used in the first order calculations and the simple diode models used in the SPICE2.G.6 analysis.

Table 3-1 Oscillator Circuit Data

	Measured Performance	First Order Calculations	SPICE2.G.6 Results
Frequency	1.98 kHz	2.022 kHz	2.022 kHz
Output Voltage Threshold for Diode Conduction	6.0 V	7.28 V	7.2 V
Peak Output Voltage	10.0 V	8.79 V	9.93 V

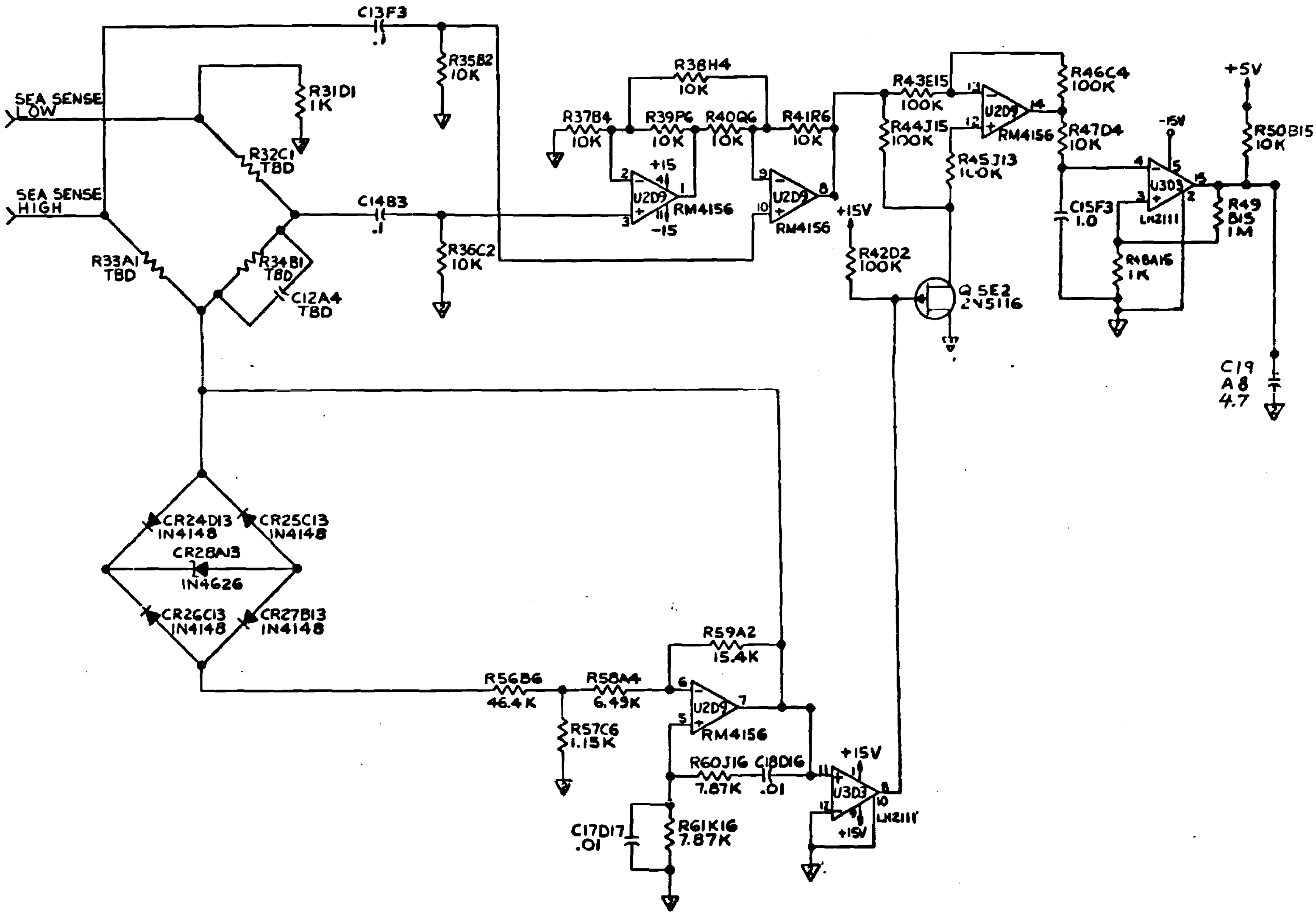


Figure 3-4 Sea Water Sensing Circuit

A more informative result is the agreement between the values for the peak output voltage. The measured peak voltage agrees with the SPICE2.G.6 result to within less than 1%. This agreement, which is much closer than for the values listed for the output threshold voltage, is achieved in spite of the simple diode models used in the SPICE2.G.6 analysis. The reduced effect of the simple diode models on the peak voltage is not surprising in view of the reduced dependence of the diode forward bias voltage on diode current at relatively high current levels. The peak output voltage predicted by the first order calculations is low by approximately 12% and is due primarily to the assumption used in the calculations that the oscillator output contains only a single frequency component. This assumption leads to the result that the voltage at the non-inverting input of the oscillator op amp shown in Figure 3-2 is given by

$$V+ = \frac{VOUT}{3} \qquad (3.27)$$

The agreement between the actual peak voltage and the calculated peak of within 12% indicates that the simple calculations presented are valid for an approximate solution.

4.0 Conclusions and Recommendations

This study demonstrated that the SPICE computer simulation program can accurately model the Wien bridge oscillator. Specifically the difference between the output amplitudes from SPICE and from experimental testing was less than 1%. The SPICE predicted and experimental signal frequencies differed by approximately 2%. Originally it was noted that the brass board oscillator was not always self-starting. A new set of resistance values were supplied by Honeywell, and these values were changed on our brass board. These new resistance values increased the loop gain and caused the test oscillator to always self start. It was noted that the higher gain did cause a more distorted sinusoidal output.

The existing parallel wire probe was shown to produce wide resistance variations depending upon water salt concentration and water volume. Our experimentations using one drop of water with different salt concentrations confirmed previous Honeywell results showing highly variable resistance values. It was not possible to obtain consistent resistance values for one drop of water regardless of its salt concentration. This was due mainly to difficulties in controlling drop size and position on the probe. Reported resistance values should be interpreted as typical rather than absolute. Furthermore, tests showed the present parallel wire could produce low resistance values with only one drop of water. However the resistance variations make it difficult to determine where the threshold should be set for sea water sense. For example, the data in Table 2-1 suggests setting a threshold resistance less than 78 ohms to insure proper sea water sense. This would still be a somewhat arbitrary level because water drop size variations and concentrations can lower this resistance further.

The alternative parallel wire probe with alternating exposed and sealed conductive regions prevents a false sea water sense with only one drop of water. Specifically the probe configuration of Figure 2-2 is recommended since it requires the presence of a larger volume of water to produce a conductive path between tracks. Establishing a proper threshold level with this probe configuration still involves some uncertanties. However, experimental data from Table 2-4 show approximately two orders of magnitude difference between sea and tap water resistancess.

Experimentation with the capacitive sensing probe of Figure 2-5 showed this approach to be feasible for sensing water volume but not capable of distinguishing between salt and fresh water. Total capacitance change was between 50 to 100 pF. Potential problems exist with this sensing technique since the 8 to 9 feet of connective wiring will produce several hundred pF of stray capacitance in parallel with the sensor. Furthermore, stray capacitance will exist between the probe tracks and the enclosure. This stray capacitance will be a function of probe position as well. These parasitic capacitance effects probably would dominate and severely limit reliable sensing using this method.

Acknowledgment

The authors wish to acknowledge the assistance provided by Curt Motchenbacher, Rick Hoyme, Paul Haefner, Dick Larson, and Mike Furlong of Honeywell in conducting this study.

Appendixes

A.1 Operational Amplifier RM4156

An operational amplifier model developed by Dr. James C. Bowers [2] was used in the SPICE2.G.6 simulations of the sea water sensing circuitry. The model subcircuit appears in Figure A-1 and includes node numbers and SPICE component names. The electrical specifications and resulting SPICE model parameters are listed in Table A-1. A sample SPICE listing of the subcircuit appears in Figure A-2.

A.2 Comparator LH2111

The operational amplifier model shown in Figure A-1 was also used for the LH2111 comparator. Table A-2 lists the LH2111 electrical characteristics and SPICE model parameters. A sample SPICE listing for the subcircuit appears in Figure A-3. The effect of an external pull-up resistor is modelled by limiting the ouput voltage swings to the approriate levels with the voltage sources VL and VH shown in Figure A-1.

[2] James C. Bowers, "Basic EMC Technology Advancement For C Systems, Macromodels of Op Amps for CADA Applications," Final Technical Report, vol II-A, Southeastern Center for Electrical Engineering Education, St. Cloud, Fla., April 1983.

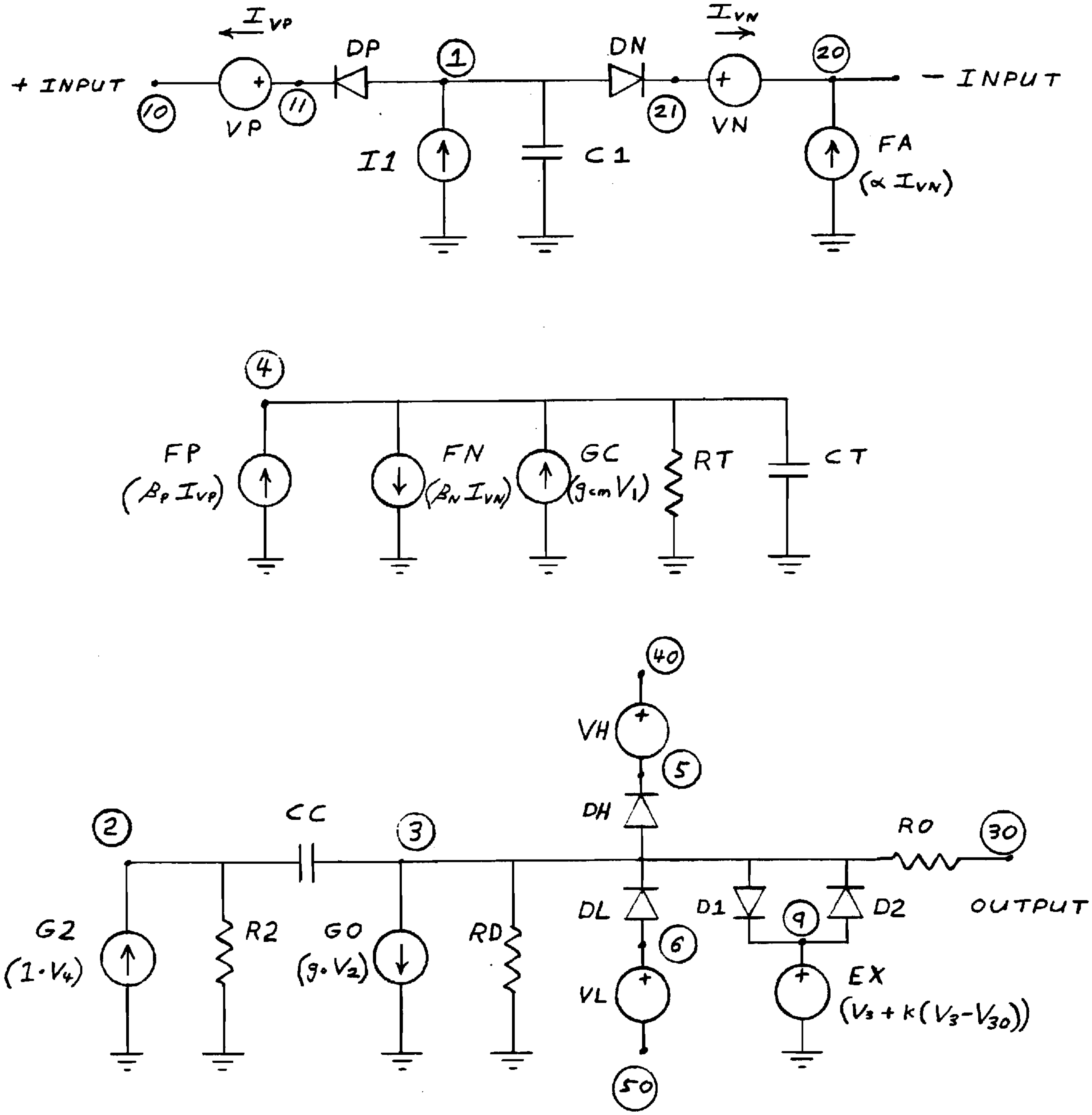


Figure A-1 SPICE Operational Amplifier Model

Table A-1 RM4156 Model Parameters

Electrical Specifications		Model Parameters
Bias Current	$I_B = 60$ nA	I1 = 81.9 nA
Offset Current	$I_{OS} = 30$ nA	VP = VN = 0 V
Offset Voltage	$V_{OS} = 1$ mV	$\alpha = 1.03$
Input Resitance	$R_{IN} = 5$ M	$\beta_P = 586$
Slew Rate	SR+ = 1.6 V/μSec	$\beta_N = 715$
	SR− = 1.6 V/μSec	C1 = 9.21 fF
Fractional Step Response		CC = 30 pF
(estimated)	$\Psi = 0.18$	$\eta = 1.54$
Open Loop Gain	$G_{OL} = 50$ kV/V	IPS = 0.01 pA
Unity Gain Bandwidth	$f_u = 3.5$ MHz	INS = 0.008 pA
High Frequency Pole	$f_2 = 5$ MHz	$V_{C1}(t=0) = 0.613$ V
(estimated)		RO = 300 Ω
Compensation Capacitor	CC = 30 pF	RD = 300 Ω
(estimated)		R2 = 100 kΩ
Output Resistance:		go = 2.52 $\mho$
AC	$R_{OAC} = 300$	gcm = 66 x10^{-9} $\mho$
(estimated) DC	$R_{ODC} = 600$	CT = 31.8 nF
Output Voltage Swing	V = 12.5 V	RT = 1.0 Ω
Output Current Limit	I_O = 15 mA	k = 0.215
		VH = 2.6 V
		VL = 2.6 V
		DP: IS = IPS, N = η
		DN: IS = IPS, N = η
		DH, DL: IS = 2.37 fA, N = 0.1
		D1, D2: IS = 10 fA, N = 1.0

```
.SUBCKT RM4156 10 20   30  40    50
*               +IN-   OUT  +SUPPLY-
*  RAYTHEON RM4156 (HARRIS HA-4156) GENERAL PURPOSE OP AMP MODEL
*      SPECIFY     .TRAN UIC     IN SPICE INPUT FILES (FOR CAP C1) UNLESS
*  DC BIAS SOLUTION IS CALCULATED (.DC OR .AC).
*INPUT STAGE
VP 11 10 0
VN 21 20 0
DP 1 11 DP
DN 1 21 DN
I1 0 1 81.9N
C1 1 0 9.21F IC=+0.613
FA 0 20 VN 1.03
*
*SECOND STAGE
FP 0 4 VP 586
FN 4 0 VN 715
GC 0 4 1 0 65.0N
RT 4 0 1.0
CT 4 0 31.3N
*
*THIRD STAGE
G2 0 2 4 0 1.0
R2 2 0 100K
CC 2 3 30P
GO 3 0 2 0 2.52
RD 3 0 300
RO 3 30 300
DH 3 5 DV
DL 6 3 DV
VH 40 5 2.6
VL 6 50 2.6
D1 3 9 D1
D2 9 3 D1
EX 9 0 POLY(2) 3 0 3 30 0 1 0.215
*
.MODEL DP D IS=1E-14 N=1.54
.MODEL DN D IS=0.8E-14 N=1.54
.MODEL DV D IS=2.37E-15 N=0.1
.MODEL D1 D IS=1E-14 N=1.0
.ENDS RM4156
```

Figure A-2 SPICE Listing for RM4156

Table A-2 LH2111 Model Parameters

Electrical Specifications	
Bias Current	I_B = 60 nA
Offset Current	I_{os} = 4 nA
Offset Voltage	V_{os} = 0.7 mV
Input Resitance	R_{IN} = 1 M
Slew Rate	SR+ = 20 V/μSec
	SR− = 24 V/μSec
Fractional Step Response (estimated)	Ψ = 0.18
Open Loop Gain	G_{OL} = 200 kV/V
Unity Gain Bandwidth	f_u = 4.8 MHz
High Frequency Pole (estimated)	f_z = 9.4 MHz
Compensation Capacitor (estimated)	CC = 1 pF
Output Resistance:	
(estimated) AC	R_{OAC} = 40
(estimated) DC	R_{ODC} = 100
Output Voltage Swing:	varies
Output Current Limit	I_O = 50 mA

Model Parameters
I1 = 117.2 nA
VP = VN = 0 V
α = 0.048
β_P = 204.77
β_N = 200.76
C1 = 0.879 fF
CC = 1 pF
η = 15.24
IPS = 0.01 pA
INS = 1.02 fA
$V_{C1}(t=0)$ = 6.17 V
RO = 40 Ω
RD = 60 Ω
R2 = 100 kΩ
go = 1110.0 ℧
gcm = 9.5 x10^{-10} ℧
CT = 16.9 nF
RT = 1.0 Ω
k = 0.522
VH = 0.85 V
VL = 15.1 V
DP: IS = IPS, N = η
DN: IS = IPS, N = η
DH, DL: IS = 42.56 fA, N = 0.1
D1, D2: IS = 10 fA, N = 1.0

```
.SUBCKT LH211A 10 20   30   40    50
*                 +IN-   OUT  +SUPPLY-
*  NATIONAL LH2111 DUAL VOLTAGE COMPARATOR (ONE HALF OF LH2111)
*      THE VOLTAGE SOURCES VH AND VL ARE SET SUCH THAT THE OUTPUT
*  IS HELD BETWEEN 0 AND 15 VOLTS (+15 AND -15 VOLT SUPPLIES).
*      SPECIFY     .TRAN UIC     IN SPICE INPUT FILES (FOR CAP C1) UNLESS
*  DC BIAS SOLUTION IS CALCULATED (.DC OR .AC).
*INPUT STAGE
VP 11 10 0
VN 21 20 0
DP 1 11 DP
DN 1 21 DN
I1 0 1 117.2N
C1 1 0 0.879E-15 IC=+6.17
FA 0 20 VN 0.048
*
*SECOND STAGE
FP 0 4 VP 204.77
FN 4 0 VN 200.76
GC 0 4 1 0 9.50E-10
RT 4 0 1.0
CT 4 0 16.9N
*
*THIRD STAGE
G2 0 2 4 0 1.0
R2 2 0 100K
CC 2 3 1P
GO 3 0 2 0 1110
RD 3 0 60
RO 3 30 40
DH 3 5 DV
DL 6 3 DV
VH 40 5 0.35
VL 6 50 15.1
D1 3 9 D1
D2 9 3 D1
EX 9 0 POLY(2) 3 0 3 30 0 1 0.522
*
.MODEL DP D IS=1E-14 N=15.24
.MODEL DN D IS=1.018E-15 N=15.24
.MODEL DV D IS=42.56E-15 N=0.1
.MODEL D1 D IS=1E-14 N=1.0
.ENDS LH211A
```

Figure A-3 SPICE Listing for LH2111

A.3 Wien Bridge Oscillator

The Wien Bridge Oscillator of Figure 3-3 was simulated using the SPICE2.G.6 program. The SPICE input file and transient analysis appear on the pages immediately following. A voltage source VSTART is used to start oscillations and provides a 100 μs 1.0 volt pulse. The transient analysis was performed over a 2 ms time frame allowing the output voltage to oscillate for approximately four periods. The peak output voltage and diode turn on voltage were recorded during the last period to minimize the effects of the pulsed source VSTART. The peak output voltage was taken at 1.82 ms and has a value of

Vmax = 9.93 V.

The output voltage at diode turn on, defined here as the output voltage when the diode bridge current is approximately an order of magnitude less than the current through the resistor R58, was determined by data at 1.51 ms:

Vout = 7.21 V

Diode Current (R56 current)
I = 25.4 μA

R58 Current I = 325 μA.

```
1****** 26 NOV 84 ******* SPICE2.G.6 3/15/83 ******* 13:04:27 *****

0OSCILLATOR CIRCUIT - OSC

0****     INPUT LISTING                          TEMPERATURE =   27.000 DEG C

0***********************************************************************



 R56 6 5 3.65K
 R57 5 0 1.33K
 R58 5 4 5.36K
 R59 4 1 15.4K
 R60 3 2 7.87K
 R61 3 0 7.87K
 C18 2 1 0.01U
 C17 3 0 0.01U
 X1  9 4 1 10 20 RM4156
 D1  1 7 DIODE
 D2  8 1 DIODE
 D3  6 7 DIODE
 D4  8 6 DIODE
 DZ1 8 7 ZENER
 VSTART 9 3 PULSE 0 1.0 20U 0 0 100U 1
 VCC 10 0 15
 VEE 20 0 -15
 .SUBCKT RM4156 10 20   30   40    50
 *                +IN-   OUT  +SUPPLY-
 *  RAYTHEON RM4156 (HARRIS HA-4156) GENERAL PURPOSE OP AMP MODEL
 *      SPECIFY      .TRAN UIC      IN SPICE INPUT FILES (FOR CAP C1) UNLESS
 *  DC BIAS SOLUTION IS CALCULATED (.DC OR .AC).
 *INPUT STAGE
 VP 11 10 0
 VN 21 20 0
 DP 1 11 DP
 DN 1 21 DN
 I1 0 1 81.9N
 C1 1 0 9.21F IC=+0.613
 FA 0 20 VN 1.03
 *
 *SECOND STAGE
 FP 0 4 VP 586
 FN 4 0 VN 715
 GC 0 4 1 0 66.0N
 RT 4 0 1.0
 CT 4 0 31.8N
 *
 *THIRD STAGE
 G2 0 2 4 0 1.0
 R2 2 0 100K
 CC 2 3 30P
 GO 3 0 2 0 2.52
 RD 3 0 300
 RO 3 30 300
 DH 3 5 DV
 DL 6 3 DV
 VH 40 5 2.6
 VL 6 50 2.6
 D1 3 9 D1
 D2 9 3 D1
 EX 9 0 POLY(2) 3 0 3 30 0 1 0 215
```

```
.MODEL DN D IS=0.3E-14 N=1.54
.MODEL DV D IS=2.37E-15 N=0.1
.MODEL D1 D IS=1E-14 N=1.0
.ENDS RM4156
.WIDTH IN=80 OUT=80
.TRAN 10U 2000U 0 5U UIC
.PRINT TRAN V(1) V(1,6) V(7,8) V(6) V(5) V(4) V(3) V(9)
.FOUR 2.02229915K V(1)
.OPTIONS LIMPTS=2001 ITL5=10000
.MODEL DIODE D CJO=4P VJ=1 BV=40.0 IBV=1.0E-3
.MODEL ZENER D CJO=4P VJ=1 BV=5.6  IBV=0.25E-3
.END
```